Nonlinear absorption in Silicon at mid-infrared wavelengths

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Abstract: We report strong nonlinear absorption in silicon at wavelengths between 2.6 µm and 4.5 µm. The results indicate that nonlinear absorption can limit the performance of silicon nonlinear waveguides in the mid infrared.

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1. Introduction

At telecommunications wavelengths (1.55 µm) it is well known that crystalline silicon is not an ideal third order nonlinear optical material because of its large two-photon absorption coefficient (2PA). This leads to a small nonlinear figure of merit ($FOM_{2PA} = n_2/\beta_{2PA}\lambda \approx 0.3$, where n_2 is the Kerr nonlinear coefficient; β_{2PA} the two photon absorption coefficient; and λ the wavelength). However beyond ≈2.2 µm, 2PA becomes insignificant and the performance of nonlinear optical devices based on silicon should improve substantially. This has already been utilized to demonstrate supercontinuum generation in silicon waveguides pumped at 2.12 µm [1]. However as 2PA decreases three-photon absorption (3PA) may limit the performance of nonlinear devices. The 3PA coefficients in silicon around 2.6µm are far from negligible and a value reported for β_{3PA} is 0.035cm^3/GW^2 [2]. This level of 3PA is troublesome because the power to produce strong nonlinear effects increases rapidly with wavelength because the nonlinear coefficient of a waveguide, $\gamma=2\pi n_2/A_{eff}\lambda$, drops due to slowly decreasing n_2 [3] and a more rapidly increasing A_{eff} which is the effective area of the waveguide mode. By 3µm, the value of γ can decrease by about an order of magnitude relative to values at 1.55µm. Beyond ≈3.3 µm, however, 3PA should also vanish and hence nonlinear absorption could become negligible. With this in mind we recently attempted to produce a mid IR super-continuum from a dispersion-engineered SOI waveguide using pump wavelengths between 3250nm and 4250nm. These experiments failed because very strong nonlinear absorption was observed and, in fact, the ≈7.5 ps long laser pulses could easily damage the input facet of the waveguide. In this paper we investigate this effect in waveguides and in bulk silicon.

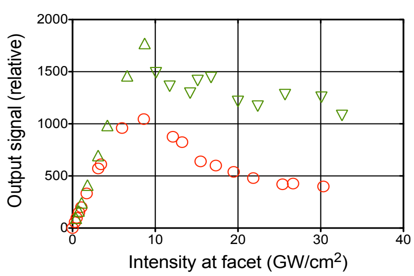

Fig.1. Transmission of a 1cm long SOI waveguide as a function of intensity at the input. Circles are for 3.25µm and triangles 4µm

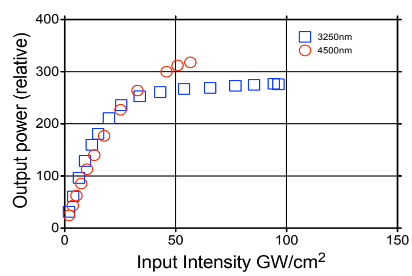

Fig. 2. Optical transmission of a 300µm thick Si wafer at 3250nm (red circles) and 4500nm (blue squares) as a function of input pulse intensity

2. Experiments

In our waveguide experiments we used the mid-IR output from a PPLN optical parametric amplifier pumped by 16 ps pulses from a Nd:YVO_4 laser and seeded by a tunable semiconductor diode laser generating 7.5 ps pulses at 1.5 MHz. The system is described in [4]. The tunable mid-IR output was coupled into 0.4 µm high by 1.7 µm wide SOI waveguide with a molded chalcogenide glass lens with NA=0.85. The waveguides were up-tapered to around 8µm at the input facet and this exceeded the diameter of the focused beam which was 3-4 µm. At low power the total insertion loss of the waveguide was ≈16-17 dB. The transmission of the waveguides was measured using a pair of PbSe detectors and the alignment of the beam to the waveguides was optimized using an InSb camera (Xenics

Onca). The spectrum of the transmitted light could also be measured with the aid of a 0.25m monochromator and a PbSe detector.

Initially we simply measured the insertion loss of the waveguide as a function of input power. A pair of curves measured at 3250 and 4000nm are shown in Fig. 1. As is apparent the output power initially rose almost linearly before abruptly decreasing. Above this transition threshold the transmission dropped rapidly reaching as low as 25% of the initial value before the facet of the waveguide damaged at a fluence ≈0.2J/cm^2. The output spectra showed increasing spectral broadening as the input power initially increased as well as evidence of parametric amplification around the pump. However, once the threshold was exceeded the spectral broadening did not increase further. This behaviour was observed over the whole transmission range of the waveguide which extended to 4.2 µm. Computer modeling suggested that a combination of multi-photon absorption, free carrier absorption and electron avalanche ionization was needed to explain these results. For picosecond pulses, free carrier effects dominate because of the carrier density required to produce strong absorption scales with λ^{-2}. In addition it is known that the threshold for avalanche ionization decreases with increasing wavelength from measured values of 0.2J/cm^2 at 1.06 µm [5].

To elucidate these effects we decided to perform experiments on bulk silicon in the form of a double side polished wafer 300 µm thick probed using ≈200 fs duration pulses produced by difference frequency generation of the outputs from a Quantronix Palitra optical parametric generator pumped by a Clark CPA2001 Ti:sapphire laser. This produced tunable radiation from ≈ 2600 nm to 4500 nm with pulse durations short enough that the free carrier effects were reduced to the point where nonlinear absorption alone could be detected.

The results are shown in Fig 2. Using the shorter pulses leads to gradual saturation of the transmission with increasing input – a characteristic of multi-photon absorption. In principle by plotting $1/T^{n-1}$ vs P^{n-1} where n is the number of photons for nonlinear absorption, straight-line plots are only obtained for one specific value of n. Unfortunately this is only true for a Gaussian beam and pulse profiles at very low levels of nonlinear absorption: in other words the curves in Fig. 2 are almost identical whether due to 3PA or 4PA. What is apparent from Fig. 2 however is that the nonlinear absorption remains strong at wavelengths well beyond the expected cut-off for 3PA although the onset of the absorption occurs at higher pulse energies as the wavelength increases.

Since we could not distinguish between 3PA and 4PA from these data we decided to analyze the wavelength dependence in terms of an effective 3PA coefficient obtaining the results of Fig. 3. This indicates that whilst the nonlinear absorption drops steadily, it never approaches zero at any wavelength within our measurement range. Since at the same time the nonlinear coefficient of the waveguide is decreasing rather rapidly, we conclude for strong nonlinear effects, such as supercontinuum generation, it will be difficult to avoid nonlinear absorption in silicon waveguides even in the mid infrared. In addition ultra-short pulses in the mid-IR will still be needed to avoid free carrier effects due to the wavelength dependence of the free carrier absorption and avalanche ionization threshold.

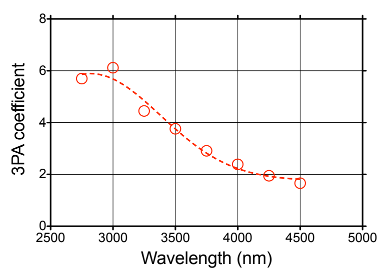

Fig. 3. The relative value of the effective 3PA absorption coefficient for a bulk Si sample irradiated at different wavelengths

5. Acknowledgements

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4. References

[1] B. Kuyken *et al*, "Mid-infrared to telecom-band supercontinuum generation in highly nonlinear silicon-on-insulator wire waveguides," Opt. Express **19**, 20173-20181 (2011).
[2] S. Pearl *at al*, "Three photon absorption in silicon for 2300–3300nm", Appl. Phys. Letts. **93**, 131102 (2008).
[3] Q. Lin *et al*, "Dispersion of silicon nonlinearities in the near infrared region", Appl. Phys Letts. 91, 021111 (2007).
[4] V. Kolev *et al,* "Compact high-power optical source for resonant infrared pulsed laser ablation and deposition of polymer materials", Opt. Express **14**, 12302-12309 (2006).
[5] P. Pronko *et al,* "Avalanche ionization and dielectric breakdown in silicon with ultrafast laser pulses" Phys. Rev. B **58**, 2387-2390 (1998)